THE HOST GALAXY OF GRB 031203: IMPLICATIONS OF ITS LOW METALLICITY, LOW REDSHIFT, AND STARBURST NATURE

Jason X. Prochaska[1], Joshua S. Bloom[2,3], Hsiao-Wen Chen[4,5], Kevin C. Hurley[6], Jason Melbourne[1], Alan Dressler[7], James R. Graham[8,9], David J. Osip[10], W.D. Vacca[11,9]
Accepted to the Astrophysical Journal: April 20, 2004

ABSTRACT

We present Keck/NIRSPEC near-IR images and Magellan/IMACS optical spectroscopy of the host galaxy of GRB 031203. The host is an actively star-forming galaxy at $z = 0.1055 \pm 0.0001$. This is the lowest redshift GRB to-date, aside from GRB 980425. From the hydrogen Balmer lines, we infer an extinction of $A_V = 3.62 \pm 0.25$ or a total reddening $E_T(B - V) = 1.17 \pm 0.1$ toward the sightline to the nebular regions. After correcting for reddening, we perform an emission-line analysis and derive an ISM temperature of $T = 13400 \pm 2000\,$K and electron density of $n_e = 300\,$cm^{-3}. These imply a metallicity [O/H] $= -0.72 \pm 0.15\,$dex and a roughly solar abundance pattern for N, Ne, S, and Ar. Integrating Hα, we infer a dust-corrected star formation rate (SFR) of $> 11 M_\odot\,$yr^{-1}. These observations have the following implications: (1) the galaxy has a low K'-band luminosity $L \approx L_K^*/5$, typical of GRB host galaxies; (2) the low redshift indicates GRB 031203 had an isotropic-equivalent γ-ray energy release smaller than all previous confirmed GRB events. The burst discovery, near the detection limit of INTEGRAL, raises the likelihood of identifying many additional low z, low flux events with *Swift*; (3) the large SFR, low metallicity, and the inferred hard radiation field is suggestive of massive star formation, supporting the collapsar model; (4) several lines of evidence argue against the identification of GRB 031203 as an X-ray flash event.

Subject headings: Gamma Rays: Bursts, Stars: Formation

1. INTRODUCTION

The study of the host galaxies of gamma-ray bursts (GRBs) plays a central role for studies of progenitor theory and afterglow observations. First, host redshifts are required to derive the burst energy and afterglow timescale and to determine the GRB rate density evolution (e.g. Djorgovski et al. 2003). Second, the host photometric properties (Sokolov et al. 2001; Chary, Becklin, & Armus 2002) together with burst locations (Bloom, Kulkarni, & Djorgovski 2002) within hosts support the notion of a progenitor population intimately connected with star formation (e.g. Paczyński 1998). It is now widely accepted that long-duration GRBs originate from the deaths of massive stars, as as suggested by Woosley (1993) and confirmed by recent observations (e.g. Bloom et al. 1999; Stanek et al. 2003; Hjorth et al. 2003). Third, limits on time-variable hydrogen- and metal-absorption in the hosts provide constraints on the physical state and chemical composition of the interstellar medium (ISM) in the vicinity of the GRBs (Perna & Loeb 1998; Draine & Hao 2002; Mirabal et al. 2003).

At the same time, long-duration GRBs present an alternative means to address a number of open questions in different sub-fields of extragalactic research related to the formation of massive stars. For example, early-time spectroscopy of GRB optical afterglows allows us to measure the metallicity and dust content of the progenitor environment through absorption line studies (e.g. Vreeswijk et al. 2001). Late-time galaxy spectroscopy of the GRB hosts allows us to study the ionization state and metallicity of the general ISM properties of host galaxies using various spectral diagnostics such as the [Ne III]/[O II] ratio (Bloom, Djorgovski, & Kulkarni 2001). Together these results could impose strong constraints on the stellar initial mass function (IMF) and chemical enrichment history of the galaxy population that hosts GRBs. Previous work presents some evidence that GRBs arise preferentially in low-metallicity environments with a top-heavy IMF (Savaglio, Fall, & Fiore 2003), which is supported by the agreement between the luminosity distribution of GRB hosts and faint blue galaxies found in the field. In addition, galaxies selected by association with GRBs are less affected by dust than those found in optical or sub-millimeter surveys (Berger et al. 2003) and therefore may be adopted to constrain the amount of obscured star-formation in the universe (Blain & Natarajan 2000; Djorgovski et al. 2003). Finally, afterglow studies of GRBs discovered in the early universe ($z \gtrsim 8$) will undoubtedly advance our understanding of the first generations of stars as well as chemical evolution in the early universe.

In this paper we report the spectroscopic identification of the host of GRB 031203 at $z = 0.1055$ and present a case study of imaging and spectral properties of the host population. The long-duration (20 sec) GRB 031203 trig-

[1] UCO/Lick Observatory, University of California, Santa Cruz, Santa Cruz, CA 95064; xavier@ucolick.org

[2] Harvard-Smithsonian Center for Astrophysics, MC 20, 60 Garden Street, Cambridge, MA 02138

[3] Harvard Society of Fellows, 78 Mount Auburn Street, Cambridge, MA 02138

[4] Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Building 37, Cambridge, MA 02139-4307

[5] Hubble Fellow

[6] University of California at Berkeley, Space Sciences Laboratory, Berkeley, CA 94720-7450

[7] Carnegie Observatories, Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101

[8] Department of Astronomy, University of California, 601 Campbell Hall, Berkeley, CA 94720-3411

[9] Visiting Astronomer, W.M. Keck Telescope. The Keck Observatory is a joint facility of the University of California and the California Institute of Technology.

[10] Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile

[11] NASA/AMES Research Center, Moffett Field, CA 94035

gered the IBIS instrument of INTEGRAL on 3 December 2003 at 22:01:28 UT with an initial localization of $2.5'$ (radius; Gotz et al. 2003). A 56k sec observation with XMM-Newton beginning at 03:52 UT on December 4, 2003 led to the discovery of an X-ray source (hereafter S1), not present in the ROSAT point source catalog (Campana et al. 2003), near the center of the INTEGRAL error circle ($\alpha = 08^h02^m30^s.19$, $\delta = -39°51'04''.0$, J2000; Santos-Lleo, M. & Calderon P. 2003). Source S1 was later reported to have faded over the first XMM pointing (Rodriguez-Pascual et al. 2003) and the refined position of S1 (Vaughan et al. 2004) is consistent with a fading radio source (Frail 2003; Soderberg, Kulkarni, & Frail 2003). Moreover, the expanding X-ray dust echo around the afterglow is consistent with a bright explosive event (in X-rays) at the position of the galaxy and coincident in time with GRB 031203 (Vaughan et al. 2004). The simplest assumption is that both the X-ray and radio transients are afterglow emission from GRB 031203.

Before the radio transient was found, several attempts were made to identify the optical afterglow (see Cobb et al. 2004). The identification of the optical transient was first reported by Hsia et al. (2003) to be within the error circle of S1, but this identification was invalidated later based on the detection of sources in the J- and F-plates of the DSS (Bloom et al. 2003b). Since the radio transient was later found to be coincident with this source and because the source appeared extended in an *I*-band image, Bloom et al. (2003a) suggested that the source was a galaxy—either in the foreground or the host of GRB 031203. Subsequent radio astrometry improved the coincidence of the radio and optical source (Soderberg, Kulkarni, & Frail 2003), confirming that this galaxy was indeed the host of the GRB (Prochaska et al. 2003a). A detailed overview of the optical astrometry of the host is presented in Cobb et al. (2004). We acquired optical spectroscopy of the galaxy on the Magellan telescopes and reported a preliminary redshift of $z = 0.105$ (Prochaska et al. 2003b). Although the host galaxy lies at low Galactic latitude and is subject to significant extinction, its proximity affords a careful examination of its properties.

We present detailed IR imaging and optical spectroscopy of the galaxy and analyze these observations to determine its luminosity, metallicity, and star formation rate. This paper is organized as follows: § 2 reviews the observations and data analysis; we perform an emission line analysis in § 3 to determine the reddening, metallicity, and relative abundances of the nebular region; and § 4 discusses the star formation rate and implications of the galaxy properties for the GRB phenomenon. Throughout this paper we will adopt a standard Λ cosmology ($H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$).

2. OBSERVATIONS AND DATA ANALYSIS

We first observed the galaxy coincident with GRB 031203, host galaxy HG 031203, on UT 2003 December 05.6 as part of on ongoing target-of-opportunity program with the Keck telescope to study GRB afterglows and GRB host galaxies. We imaged the field using the slit viewing camera (SCAM) of NIRSPEC (McLean et al. 2000) in the N3 ($\sim$ *J*-band), N5 ($\sim$ *H*-band) and K' filters for total exposure times of 540s each. The observations in each bandpass
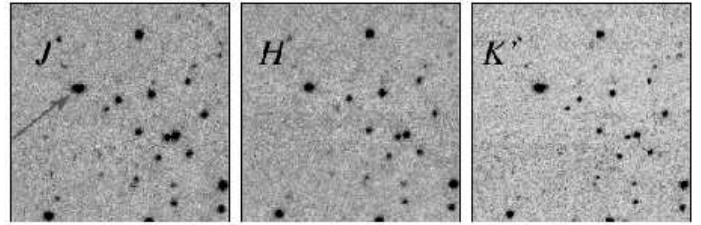

FIG. 1.— SCAM images obtained with the NIRSPEC instrument on the Keck II telescope on 2003 December 05.6. The arrow designates the host galaxy studied in this paper. The field of view is $\approx 46'' \times 46''$ with orientation N up and E left and the pixel size is $0.183''$ on a side.

were composed of nine sets of two to six exposures, 10-30 seconds in duration with dither offsets of between $6''$ and $9''$ in space to remove hot pixels. The coadded images are displayed in Figure 1. Although the images were acquired at large airmass owing to the low declination of the field, the seeing ranges from FWHM $\approx 0.65''$ to $0.5''$ from *J* to K'. The images clearly identify a galaxy whose center lies within $1''$ of the nominal centroid of the radio position for GRB 031203 (Soderberg, Kulkarni, & Frail 2003). An elliptical fit to the isophotes yields a PA angle of -8 degrees and an ellipticity $\epsilon = 0.23$.

The images were calibrated with observations of the Persson standard star SJ 9132 (Persson et al. 1998) and we believe the conditions were photometric. The detection limit of the K' image is 20.2 over a $1''$-diameter aperture at the 5σ significance level. The galaxy has $J = 18.28$, $H = 17.79$, and $K' = 16.54$. Errors in the flux measurements are ≈ 0.02 mag and are dominated by systematics such as bias subtraction and aperture correction.

The following night (2003 December 06.3) we obtained a spectrum of HG 031203 using the recently commissioned IMACS spectrometer (Bigelow & Dressler 2003) on the Magellan/Baade 6.5 m telescope. We acquired three exposures totaling 2400s during twilight using the 300 line grating centered at 6600 Å with a $0.75''$ slit. In this mode, the instrument delivers a 7 pixel resolution element of FWHM ≈ 5 Å. The data were acquired near transit at an airmass ≈ 1.02 and we expect slit losses due to atmospheric dispersion are minimal. The data are wavelength calibrated and the final wavelength array is converted to a vacuum scale and corrected to the helio-centric restframe. Finally, we calibrate the observed fluxes using a spectrophotometric standard (LTT 9491) taken during the start of this photometric night. We expect a relative flux error of $< 10\%$ from the calibration of the spectrophotometric standard, but the absolute flux of the GRB host is presumably underestimated owing to slit losses (i.e. the galaxy overfilled the $0.75''$ slit).

The coadded spectrum is presented in Figure 1. The galaxy shows several strong emission lines – Hα, Hβ, [OIII], [SII] – as well as a series of positive detections including the [OII] doublet (unresolved), Hγ, Hδ, [OIII] 4363, and [NeIII] 3970. For each line, we fit a Gaussian to the emission line profile to measure the line centroid. From the five strongest emission features, we derive a redshift, $z = 0.1055 \pm 0.0001$, where the uncertainty is dominated by systematic uncertainty (i.e. the line profile is not strictly
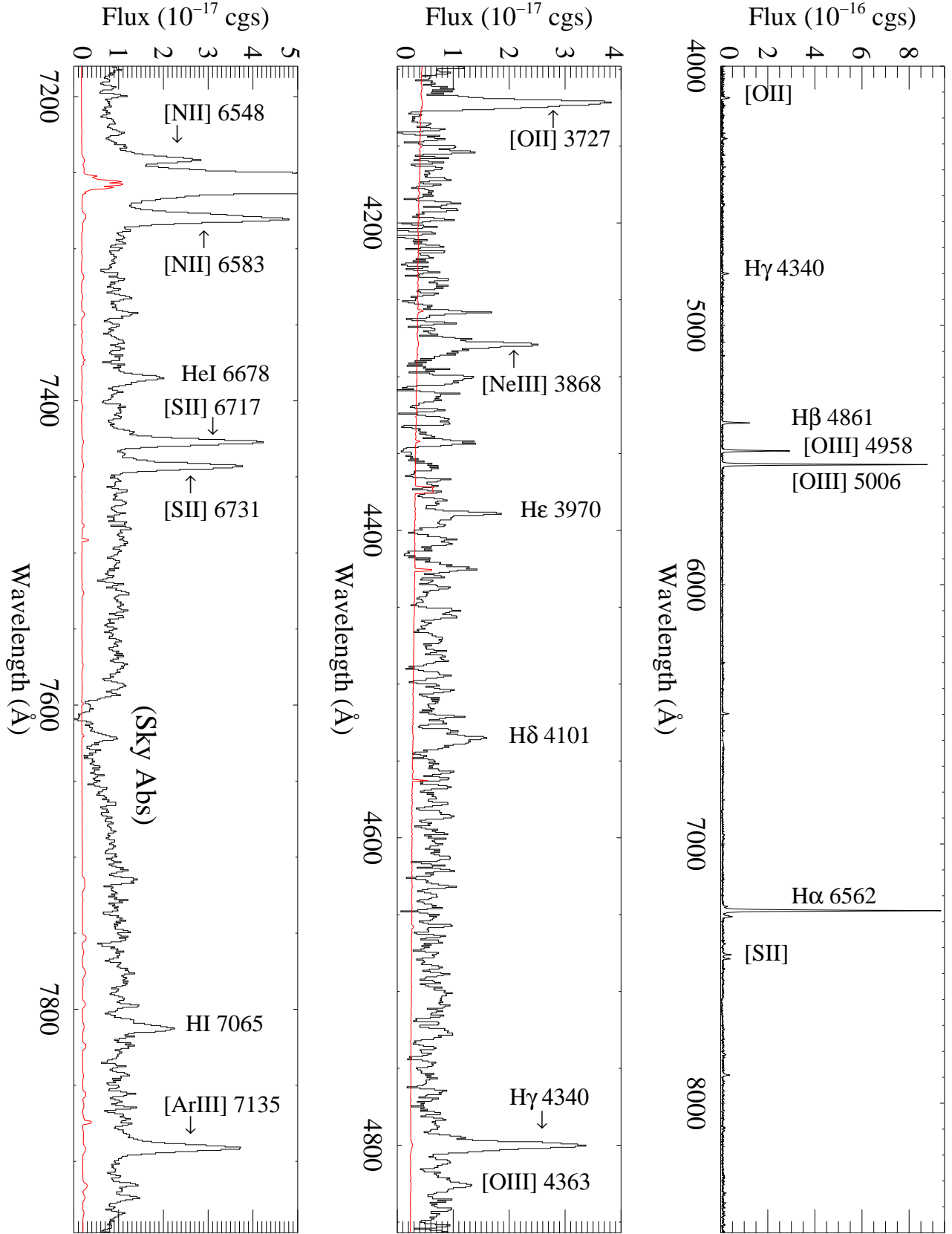
FIG. 2.— Magellan/IMACS spectrum of the host galaxy of GRB 031203. The spectrum has a FWHM ≈ 5Å resolution. The lower two panels have been smoothed by 3 pix ($\approx 1/2$ resolution element) for presentation purposes only. The strong emission line features are centered at $z = 0.1055 \pm 0.0001$ and provide measurements of the extinction and the nebular temperature, density, metallicity and SFR. Note the detections of [NeIII] $\lambda 3868$ and [OIII] $\lambda 4363$ as well as the low [OIII]/Hβ ratio. Together these observations imply a relatively hard radiation field dominated by massive stars and a metal-poor gas. The strong Hα emission corresponds to a SFR of $> 10 M_\odot \mathrm{yr}^{-1}$.

TABLE 1
EMISSION LINE SUMMARY

Ion	$\lambda_{\rm rest}$ (Å)	$\lambda_{\rm obs}$ (Å)	F_λ (10^{-16} cgs)	$EW_{\rm rest}$ (Å)	$F_\lambda/F_{\rm H\beta}$	$L_{\rm ion}$ (10^{41} cgs)
[OII]	3727.26	4121.96	1.57 ± 0.13	38.14 ± 2.02	1.0607	5.37
[NeIII]	3869.84	4278.95	1.01 ± 0.09	28.03 ± 1.68	0.6043	3.06
[NeIII]	3970.00	4388.82	0.43 ± 0.08	16.33 ± 1.31	0.2326	1.18
Hδ	4102.90	4535.43	0.53 ± 0.08	21.05 ± 1.22	0.2493	1.26
Hγ	4341.69	4799.94	1.39 ± 0.07	32.22 ± 1.03	0.4946	2.50
[OIII]	4364.44	4825.86	0.32 ± 0.06	12.96 ± 0.87	0.1107	0.56
Hβ	4862.70	5375.60	5.18 ± 0.08	90.72 ± 1.10	1.0000	5.06
[OIII]	4960.29	5483.52	12.07 ± 0.11	195.15 ± 1.56	2.1108	10.68
[OIII]	5008.24	5536.50	38.09 ± 0.19	585.04 ± 2.76	6.3565	32.15
HeI	5877.28	6497.42	1.37 ± 0.06	37.24 ± 0.79	0.1199	0.61
[OI]	6302.04	6966.53	0.35 ± 0.05	15.55 ± 0.56	0.0244	0.12
[SIII]	6312.75	6979.26	0.24 ± 0.05	13.61 ± 0.55	0.0165	0.08
[NII]	6549.91	7241.21	1.03 ± 0.05	22.03 ± 0.61	0.0630	0.32
Hα	6564.63	7256.84	46.32 ± 0.20	550.74 ± 2.31	2.8167	14.25
[NII]	6585.42	7279.71	2.52 ± 0.05	47.78 ± 0.84	0.1514	0.77
[SII]	6718.95	7426.78	1.52 ± 0.06	27.65 ± 0.56	0.0853	0.43
[SII]	6733.16	7442.63	1.28 ± 0.05	23.41 ± 0.53	0.0714	0.36
[ArIII]	7136.97	7890.79	1.50 ± 0.08	34.64 ± 0.80	0.0681	0.34

Note. — Observed wavelengths in column 3 have been air-to-vacuum corrected and are heliocentric. The flux F_λ and equivalent width values are as observed while the flux ratios $F_\lambda/F_{\rm H\beta}$ and luminosities L_{ion} have been corrected for extinction assuming $E_T(B-V) = 1.17$ (see text).

Gaussian). At this redshift, the luminosity distance to the galaxy is $487.4\,h_{70}^{-1}$ Mpc, where $h_{70} = H_0/(70 \text{ km s}^{-1}\text{Mpc}^{-1})$, and $1''$ represents $1.93\,h_{70}^{-1}$ kpc in projection. This measurement marks GRB 031203 as the lowest redshift event to date aside from the anomalous GRB 980425 (Pian et al. 2000). We also measure the emission line-width to be $\sigma = 95 \pm 15$ km s^{-1} which is consistent with the instrumental resolution. Finally, we sum the line flux and equivalent width off the local continuum; these values and the statistical errors are listed in Table 1.

3. EMISSION LINE DIAGNOSTICS

In this section, we examine the observed emission line ratios to derive integrated physical characteristics of the nebular regions within the host galaxy HG 031203. We first estimate the extinction correction necessary for deriving total line fluxes of the observed emission line. HG 031203 is located $\approx 4.7°$ off the Galactic plane and has an inferred reddening value $E_G(B-V) \approx 1.04$ (Schlegel et al. 1998). Furthermore, there may be dust along the sightline in the emission line region of the host galaxy. Therefore, the observed line ratios must be corrected for reddening. Following standard practice, we assess the extinction through comparisons of the Balmer line ratios under the assumption of Case B recombination (e.g. Osterbrock 1989; Izotov, Thuan, & Lipovetsky 1994) and a Galactic extinction law A_λ/A_V which is parameterized by $R_V \equiv A_V/E(B-V)$ (Cardelli, Clayton, & Mathis 1989). Assuming $R_V = 3.1$ for both our Galaxy and the sightline through HG 031203 and also adopting a single extinction law[12], we derive $A_V = 3.62 \pm 0.25$ which gives a self-consistent solution to the relative line strengths of Hα,

[12] The redshift of HG 031203 which differs from $z = 0$, implies that the extinctions are not strictly additive; however, this has a minor effect on the total extinction analysis.

Hβ, Hγ, and Hδ and implies a total $E_T(B-V) = 1.17\pm0.1$. Although this value is consistent with the far-IR measurement reported by Schlegel et al. (1998), several authors have argued that the far-IR analysis overestimates the $E_G(B-V)$ value by a factor of $\approx 30\%$ (e.g. Dutra et al. 2003). The Dutra et al. analysis recommends scaling the Schlegel et al. (1998) value by 0.75 and therefore one calculates a value of $E_G(B-V) = 0.78$ for the sightline to HG 031203. In this case, it is likely ($> 3\sigma$) that there is modest extinction ($A_V \approx 1$) associated with the host galaxy. On the other hand, it is possible that systematic errors in the Schlegel et al. analysis could lead to an underestimate of the reddening (Finkbeiner 2004, priv. comm.). In the following analysis, we adopt a Galactic reddening $E_G(B-V) = 0.78$ and note this may be considered a lower limit. Of course, the emission line analysis is only sensitive to the total reddening $E_T(B-V)$ and we consider this well constrained for our adopted R_V value and extinction law. The extinction corrected flux ratios and luminosities are presented in columns 5 and 6 of Table 1. We note that a more comprehensive analysis of the differential extinction (e.g. the introduction of multiple extinction laws, variations in R_V) lies both beyond the scope of this paper and dataset, and such an analysis would be sensitive to additional uncertainties including absorption from stars within HG 031203 and the exact temperature of the nebular regions.

Next, we assess the physical origin of the emission lines, whether they arise in an H II region, as a result of an active galactic nucleus (AGN), or both. A comparison of the measured [OIII]/Hβ, [SII]/Hα, [OII]/Hβ, and [OI]/Hα ratios to those from samples of HII galaxies and AGN presented by Rola, Terlevich, & Terlevich (1997) and Kennicutt (1992) indicate the spectrum of HG 031203 is dominated by nebular emission. Specifically, AGN show high

[S II] $\lambda\lambda6718, 6733$/Hα and [N II] $\lambda6583$/Hα flux ratios relative to [O III] $\lambda5008$/Hβ whereas HG 031203 exhibits $\log([S II] \lambda\lambda6718, 6733$/H$\alpha) = -1.25$ and $\log([N II] \lambda6583$/H$\alpha)$ -1.27. These ratios are similar to those generally associated with starbursting galaxies, indicating the spectral features are indeed diagnostics of the star-forming regions that are intimately connected to the GRB progenitor environment. Finally, as noted above, the lines are not significantly broadened but instead show a line-width consistent with the instrumental resolution.

Next, we determine various physical parameters of the star-forming region in HG 031203. To gauge the thermal conditions of the nebular gas, we implement the IRAF package NEBULAR (Shaw & Dufour 1995) assuming a two-zone model (low and moderate temperature). The [SII] $\lambda\lambda6717, 6731$ doublet provides an assessment of the electron density in the low temperature zone and the relative emission line strengths of the [OIII] lines yields a measurement of the temperature in the moderate temperature zone. We find $n_e \approx 300 \, \mathrm{cm}^{-3}$ and adopt this value for both zones. We then derive a temperature for the moderate zone $T_{med} = 13400 \pm 2000$K and we assume $T_{low} = 12900$K based on the prescription suggested by Skillman et al. (1994). The electron density is well constrained by our observations, while the temperatures are less certain owing to uncertainties in extinction and the lower signal-to-noise ration of the [O III] $\lambda4363$ line. Allowing for these uncertainties, we derive an oxygen abundance [O/H] $= -0.72 \pm 0.15$ dex (90% c.l.) assuming $\log(\mathrm{O/H})_\odot + 12 = 8.74$ (Holweger 2001).
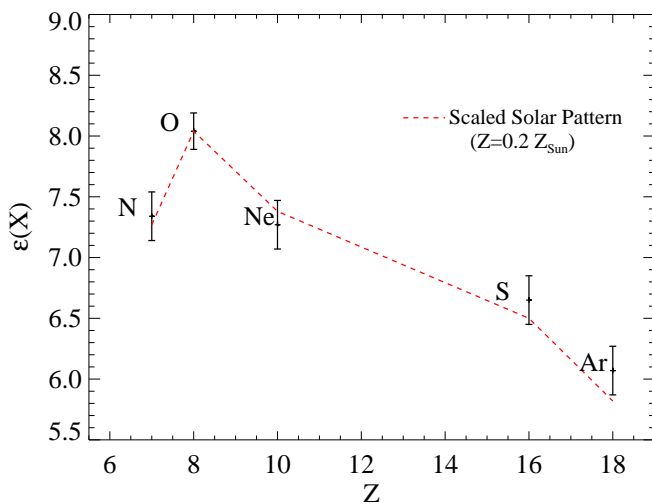

FIG. 3.— Abundance pattern of the emission-line regions of HG 031203. The dashed line traces the Solar abundance pattern which has been scaled to the galaxy's oxygen abundance ($\log(\mathrm{O/H})$ + 12 = 8.1). We find no significant deviations from the solar pattern for HG 031203.

Finally, we measure relative elemental abundances for N, Ar, Ne, and S after adopting the ionization corrections advocated by Izotov, Thuan, & Lipovetsky (1994) and solar relative abundances (Grevesse et al. 1996; Holweger 2001). We find: [N/O] $=+0.07$, [Ne/O] $= -0.11$, [S/O] $= +0.15$, and [Ar/O] $= +0.25$. The uncertainty in these values is ≈ 0.2 dex and all of the values are con-

sistent with a solar pattern (Figure 3). This matches our expectation for the various α-elements and the measurements further support a low metallicity for HG 031203. We note, however, that the [N/O] value is $\approx 2\times$ larger than expected given the sub-solar metallicity (e.g. Henry, Edmunds, & Köppen 2000). It is possible that we are underestimating the continuum level near the [N II] $\lambda\lambda6544, 6585$ lines owing to the very strong Hα line and therefore are overestimating the N abundance.

4. DISCUSSION

4.1. *Luminosity, Metallicity, and Star Formation Rate*

Even with nearly one magnitude of foreground extinction at 1μm, HG 031203 offers a rare opportunity to study the large-scale environment of a nearby GRB event. Our analysis of the nebular region of HG 031203 reveals a metal-poor, star-forming galaxy. We can combine our extinction analysis with the apparent near-IR magnitudes and the redshift of HG 031203 to assess the luminosity of the old stellar population within the galaxy. Adopting a Galactic reddening of $E_G(B - V) = 0.78$ (see above), we derive extinction corrections of 0.67, 0.45, and 0.28 magnitudes for the J, H and K' bands respectively. Adopting the standard Λ cosmology, $z_{gal} = 0.1055$ and a k-correction of -0.2 mag, we calculate absolute magnitudes of -21.20, -21.47, and -22.35 mag in JHK' respectively. The resulting K' luminosity is $+1.9$ mag fainter than $M(K)_*$ at $z = 0$ (Cole et al. 2001), i.e., the galaxy has a low luminosity ($L \approx L_K^*/5$) and presumably a low total mass. In these respects, HG 031203 is a relatively ordinary, faint galaxy. The K'-band luminosity is consistent with the median absolute K magnitude compiled by Le Floc'h et al. (2003) for GRB host galaxies. Apparently, these galaxies are, as a class, underluminous in terms of their old stellar population.

The galaxy is notable, however, for a large star formation rate (SFR). With our spectroscopic observations, we infer the SFR from the integrated, extinction-corrected Hα luminosity (Table 1). Adopting the Hα relation given by Kennicutt (1998),we find SFR(Hα) $= 11 \, \mathrm{M}_\odot \mathrm{yr}^{-1}$. We believe the uncertainty in SFR(Hα) is dominated by uncertainties in the SFR calibration which Kennicutt (1998) estimates to be $\approx 30\%$. We also attempt to infer the SFR from the dust-corrected [OII] luminosity using the comprehensive prescription described by Kewley, Geller, & Jansen (2004). Unfortunately, their analysis is only applicable to emission-line regions with $\log(\mathrm{O/H})$ $+12 > 8.2$ (Kewley, priv. comm.); the SFR corrections diverge at the nominal metallicity of HG 031203 (see their Figure 9)[13]. In addition, the [OII] lines have greater sensitivity to the dust corrections and much poorer SNR than the Hα emission. Therefore, we consider only the SFR value implied by Hα. We stress that this SFR value should be considered a lower limit to the total SFR because (i) the galaxy is larger than the slit used and (ii) the galaxy may contain regions of star formation which are enshrouded in dust. The latter effect is presumably small for this relatively metal-poor galaxy while the former effect may increase the SFR by up to

[13] These points not withstanding, we caution the reader that SFR values, irrespective of reddening corrections, derived for other GRB hosts based on the [OII] lines alone may have uncertainties of > 100%, especially if the metallicity is poorly constrained.

50%. Indeed it will be of interest to measure the late-time radio and sub-mm flux from this galaxy to assess the level of obscured star formation and compare long-wavelength emission of this host with GRB hosts at higher redshifts (following Berger et al. 2003).

To qualitatively assess the nature of star formation for HG 031203, we would like to contrast its characteristics with local samples. One simple comparison is the rest-frame equivalent width of the Hα line. For HG 031203, we measure $\mathrm{EW}_{\mathrm{rest}}(\mathrm{H}\alpha) = 550.7 \pm 2.3$Å which is significantly larger than normal, star-forming galaxies (Jansen et al. 2000; Nakamura et al. 2004). This large value suggests a system undergoing a short, very intense burst of star formation.

Another valuable diagnostic is the ratio of SFR to total luminosity. Unfortunately, there is no large, single survey to date which has compared SFR and near-IR luminosity. We therefore estimate the B-band luminosity from the measured continuum flux at $\lambda_{obs} \approx 4500$Å. We observe $F_{4500} = 8.0 \times 10^{-18}$ ergs/s/cm^{-2}/Å which translates to a Vega magnitude $B = 18.1$ mag, consistent with the detection of the galaxy in the DSS-J plate (Bloom et al. 2003b). Adopting $E_G(B-V) = 0.78$, we impose a dust correction of 3.1 mag and derive an absolute magnitude $M_B = -19.3$. We stress that this luminosity is likely an underestimate of the total B-band light because the galaxy overfilled the $0.75''$ slit. Furthermore, this $E_G(B-V)$ value may be an underestimate (see the discussion in §refsec-emiss). We compare the measured Hα/B-band luminosity of HG 031203 against the KPNO International Spectroscopic Survey, an emission-line survey of galaxies with $z < 0.095$ selected in low-dispersion objective-prism spectra (Salzer et al. 2000). Restricting our comparison to those galaxies with accurate measurements of $L(\mathrm{H}\alpha)$ and M_B (Gronwall et al. 2004), we note HG 031203 falls at the upper end of the distribution, i.e. its SFR is $\approx 5\times$ higher than galaxies with similar B-band luminosity. A portion of this offset could be explained by correspondingly higher slit losses for the B-band light than Hα and/or a higher $E_G(B-V)$ value. These corrections not-withstanding, we suspect the galaxy has a higher than average SFR per unit B-band luminosity than other local galaxies.

We can also place HG 031203 on the metallicity/luminosity locus of KISS galaxies (Melbourne & Salzer 2002). HG 031203 lies below the entire distribution. Furthermore, it falls $\Delta(\mathrm{O/H}) \approx -0.9$ dex or $\Delta M_B \approx -2$ mag off their fit to the KISS sample even if we adopt $M_B = -19.3$ mag. We speculate this offset is characteristic of a very young star forming region. Perhaps we have observed the galaxy prior to the production and/or distribution of significant metals into the nebular regions. Indeed, a similar effect is observed for the star-bursting Lyman break galaxies at high redshift (Pettini et al. 2001; Shapley et al. 2004).

4.2. *The case for identifying HG 031203 as the host galaxy of GRB 031203*

The conclusions drawn in the following subsections hinge on the identification of HG 031203 as the host galaxy of GRB 031203. In particular, this sets the redshift of GRB 031203 based on the observed emission lines of HG 031203. Before proceeding, therefore, we review the evidence for this allegation. First, Soderberg, et al. (2004) and Rodriguez-

Pascual et al. (2003) respectively have localized fading radio and x-ray sources within the half-light radius of HG 031203 (see Cobb et al. 2004). Integrating the K-band number density function of Chen et al. (2004) to $K' = 16.5$, the number density of galaxies is $7.7 \times 10^{-5}/\square''$. Therefore, the likelihood of laying within $2''$ of a galaxy at least as bright as HG 031203 is $< 0.1\%$. Second, HG 031203 has a K'-band luminosity typical of the GRB host galaxy distribution (Le Floc'h et al. 2003).

Third, this galaxy exhibits a SFR ($> 10 M_\odot \mathrm{yr}^{-1}$) which is $> 98\%$ of all galaxies at $z \lesssim 0.1$ (Nakamura et al. 2004). This argument is independent of the apparent magnitude and, furthermore, we note that the SFR is comparable to that of other GRB hosts (e.g. Berger et al. 2003). Fourth, the galaxy is metal-poor, a trait frequently attributed to GRB host galaxies. Fourth, HG 031203 exhibits a lower metallicity than $> 99\%$ of all galaxies with $M_B < -19.3$ mag (Melbourne & Salzer 2002; Lamareille et al. 2004). Again, GRB hosts appear to be metal-poor in general. Finally, there is recent evidence that a supernova was associated with GRB 031203 with a location coincident with HG 031203 (Thomsen et al. 2004; Cobb et al. 2004; Gal-Yam et al. 2004). Although none of these points can be considered a definitive argument for associating HG 031203 with GRB 031203, together they present a very strong case for a physical connection between GRB 031203 and HG 031203.

4.3. *The Energetics of GRB 031203 and Arguments against an X-ray Flash*

The fluence in the prompt gamma-ray emission in GRB 031203 has not yet been reported. To estimate this quantity, we fit the INTEGRAL SPI-ACS light curve[14] with a double exponential (single pulse). Assuming Poisson weighting, scaling the reported peak flux to 1.3×10^{-7} erg cm^{-2} s^{-1} (20–200 keV), and assuming that the IBIS *count* rate is dominated by the photons in this low energy range, we estimate the fluence to be $(4 \pm 1) \times 10^{-7}$ erg cm^{-1} (20–200 keV). This assumes a combined uncertainty of 25% in the peak flux and integrated (model) light curve. We can estimate the prompt isotropic-equivalent energy release E_{iso}(20–2000 keV) by assuming a k-correction to rest-frame (20–2000 keV) from an ensemble of bright bursts: $k = 2.6 \pm 0.9$. We find E_{iso}(20–2000 keV) $= (2.6 \pm 1.1) \times 10^{49} h_{70}^{-2}$ erg with a plausible maximum of $\approx 5 \times 10^{49}$ erg if the burst was spectrally hard ($E_0 = 1000$ keV). This is nearly identical to an independent estimation by Watson et al., who found (under a differing set of assumptions) E_{iso}(20–2000 keV) $= 2.6 \times 10^{49} h_{70}^{-2}$ erg (scaling to our chosen value of Hubble's constant).

As noted in Watson et al. (2004), this value of E_{iso}(20 – 2000 keV) is about 30 times fainter than that inferred in the (geometry corrected) prompt emission of other cosmological GRBs (Bloom, Frail, & Kulkarni 2003). If this burst was collimated, then the true energy release in the γ-ray bandpass was even lower. Soderberg et al. (2003) also pointed out that the kinetic energy in the blastwave, as proxied by the X-ray afterglow emission, was 10^3 times lower than other GRBs at comparable times (Berger al. 2003). These two results seem to suggest that the total energy in the relativistic component was substantially

---

[14] http://isdc.unige.ch/cgi-bin/cgiwrap/~beck/ibas/spiacs/ibas_acs_web

lower than the other cosmological GRBs.

Watson et al. (2004) have suggested that GRB 031203 may be an X-ray flash based upon analysis of the dust echo. However, since the occurrence of a bright soft X-ray component to the prompt burst has not been firmly established, we consider the XRF possibility less likely than Watson et al. (2004). We note that the Watson et al. argument rests on two points. First, that the ratio of the 0.2-10 keV *fluence* (estimated from the dust echo) to the 20-200 keV fluence (estimated from the *peak flux* of the GRB) yields a reliable power law index. And second, that the detection of this burst at energies $\gtrsim 100$ keV by the INTEGRAL SPI-ACS is consistent with the spectral slope estimate. We caution however that the first point mixes fluences and peak fluxes and cannot take any possible spectral evolution into account; until a reliable time-integrated spectrum above 20 keV is given, this procedure is subject to considerable uncertainty. And contrary to claim of Watson et al. we believe that the spectrum derived from this procedure cannot be said to be consistent with the SPI-ACS response. Indeed, the ACS threshold is not well-defined, as it varies along the collimator, and blocking by INTEGRAL instruments for various angles complicates the response considerably. There is at present no accurate calibration of the ACS. Thus we believe that it is impossible to confirm or disprove the X-ray rich burst hypothesis based on either argument.

Vaughan et al. (2004) have reported a dust scattered X-Ray halo from *XMM-Newton* observations taken six hours after the burst. Comparing the spectral shape of the halo with the afterglow, they inferred a hydrogen column density $N_H = 8.8 \pm 0.5 \times 10^{21}$ cm^{-2} consistent with the Parkes 21cm observations along this sightline (McClure-Griffiths et al. 2001). Vaughan et al. (2004) then estimated a time-integrated X-ray flux by assuming $A_V = 2$ mag, a value $4.4\times$ smaller than out total derived extinction. We caution, therefore, that they may have overestimated the X-ray flux in their analysis. Thus, we suggest GRB 031203 is most like GRB 980425, i.e. a low-redshift underluminous burst associated with a supernova. In this respect, it is interesting to note the single pulse nature of the burst (Bloom et al. 1998), which may be related to the emission mechanism.

4.4. *Implications for the GRB event*

Collapsars (Woosley 1993), the leading scenario for long-duration GRBs, requires a connection between the instantaneous ($\lesssim 10^7$ yr) star-formation and the probability of bursting (Bloom et al. 1998; Fryer, Woosley, & Hartmann 1999). This model describes the GRB progenitor as a massive star ($> 30 M_\odot$ at zero-age main sequence) which loses all of its hydrogen envelope and most of the helium. Importantly, MacFadyen & Woosley (1999) noted that low metallicity favors a collapsar event because low metallicity decreases mass loss leading to a more massive, more rapidly rotating star, i.e. characteristics necessary to make a disk and black hole. Examining HG 031203 in this context, we note: (i) the presence of [NeIII] emission; (ii) O^{++} is the dominant oxygen ion for the full range of extinction and temperatures considered; and (iii) the emission line regions have a significantly sub-solar metallicity. Points (i),(ii) indicate the presence of a relatively

hard radiation field. That is, massive stars ($> 30 M_\odot$) contribute significantly to the spectral energy distribution of the host. Furthermore, point (iii) follows the assertion of MacFadyen & Woosley (1999) that the collapsar event is more easily achieved in lower metallicity systems. This point is accentuated by the fact that the system has a lower than average metallicity given its B-band luminosity. Together, these observations of HG 031203 lend support to the collapsar model for GRB's.

Aside from the anomalous GRB 980425, the only other long duration GRB with a known low redshift ($z < 0.2$) is GRB 030329 (see Lipkin et al. 2003, for a review). The discovery of GRB 031203 at such a low redshift has several important implications. First, it indicates the likelihood of many additional low redshift GRB events at low flux/fluence levels. Since so few low redshift bursts had been discovered in the past 6 years (1 out of $\sim$100 well-localized GRBs) and the peak flux of GRB 030329 was more than two orders of magnitude over the detection threshold, on probabilistic grounds, Price et al. (2003) suggested that bursts with redshifts as low as GRB 030329 would be rare even in the *Swift* era (see also Schmidt 1999). The low redshift discovery of GRB 031203, however, requires a redress of this conclusion. Second, the peak flux of 1.3×10^{-7} erg cm^{-2} s^{-1} (Mereghetti & Gotz 2003, 20–200 keV;) implies that GRB 031203 was one of the faintest rapid and well-localized bursts to date. While there is still some uncertainty in the k-corrections, it appears that the *prompt* isotropic-equivalent energy of GRB 031203 appears to bridge the gap between the anomalous 980425 and the remainder of the bursts (see also Soderberg et al. 2003). Again, we point out that 031203 is distinguished from other low-energy GRBs (030329, 980326, etc.; Bloom, Frail, & Kulkarni 2002) in that the energy of 031203 in soft γ-rays (20–2000 keV) appears low even before (the unknown) geometry correction. Given the uncertainties related to estimations of the energy release in prompt X-rays, the total energy budget of the burst is rather uncertain. Analysis of the radio afterglow (Soderberg, et al. 2004) may eventually yield a tighter constraint on the total kinetic energy of the ejecta. Lastly, given the low volume associated with the universe at $z \lesssim 0.1$, one surmises that the frequency distribution of GRB energies likely increases to lower energy. This may be naturally explained as the effect of viewing angle to the GRB event (e.g. Woosley, Eastman, & Schmidt 1999), but could also be the result of an intrinsically broad distribution of GRB luminosities (e.g. Kouveliotou et al. 2004). In either case, the discovery of GRB 031203 significantly increases the likelihood of detecting many additional low z, low energy GRB events with the launch of *Swift*.

Note Added After Original Submission: Newly surfaced γ-ray satellite data in Sazonov, Lutovinov, & Sunyaev (2004) (recently relayed in Gal-Yam et al. 2004), appears to exclude the XRF hypothesis. This confirms our prior inferences — that this event was a low-luminosity GRB and not an XRF — presented in section 4.3.

REFERENCES

Berger, E., Cowie, L.L., Kulkarni, S.R., Frail, D.A., Aussel, H., & Barger, A.J. 2003, ApJ, 2003, 588, 99
B. C. Bigelow & A. Dressler 2003, SPIE, 4841, 1727
Blain, A.W. & Natarajan P. 2000, MNRAS, 312, L35
Bloom, J.S., Kulkarni, S.R., Harrison, F., Princet, T., Phinney, E.S., & Frail, D.A. 1998, ApJ, 506, L105
Bloom, J.S., et al. 1999, Nature, 401, 453
Bloom, J.S., Djorgovski, S.G., & Kulkarni, S.R. 2001, ApJ, 554, 678
Bloom, J.S., Frail, D.A., & Sari, Re'em 2001, AJ, 121, 2879
Bloom, J.S., Kulkarni, S.R., & Djorgovski, S.G. 2002, AJ, 123, 1111
Bloom, J.S., Frail, D.A., & Kulkarni, S.R. 2003, ApJ, 594, 674
Bloom, J. S., Bailyn, C., Buxton, M., Cobb, B., Dokkum, P. v. & Gonzalez, D. 2003, GCN Circ. 2481 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2481.gcn3)
Bloom, J. S., Bailyn, C., & Dokkum, P. v. 2003, GCN Circ. 2472 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2472.gcn3)
Campana, S., Tagliaferri, G., Chincarini, G., Covino, S., Fugazza, D., & Stella, L. 2003, GCN Circ. 2478 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2478.gcn3)
Cardelli, J.A., Clayton, G.C., & Mathis, J.S. 1989, ApJ, 345, 245
Chary, R., Becklin, E.E., & Armus, L. 2002, ApJ, 566, 229
Chen, H.-W. et al. 2004, in preparation
Cobb, B.,E., Bailyn, C.D., van Dokkum, P.G., Buxton, M.M., & Bloom, J.S. 2004, ApJ, submitted (astro-ph/0403510)
Cole, S. et al. 2001, MNRAS, 326, 255
Diplas, A. & Savage, B. D. 1994, 427, 274
Djorgovski, S. G., Kulkarni, S. R. ,Frail, D. A., Harrison, F. A., Bloom, J. S., Berger, E., Price, P. A., Fox, D., Soderberg, A. M. and Galama, T. J., Reichart, D. E., Sari, R., Yost, S. A., Mahabal, A., Castro, S. M., Goodrich, R., & Chaffee, F. H. 2003, in Discoveries and Research Prospects from 6- to 10-Meter-Class Telescopes II. Proceedings of the SPIE, P. Guhathakurta (ed.), SPIE, v. 4834, p. 238
Draine, B.T. & Hao, L. 2002, ApJ, 569, 780
Dutra, C.M., Ahumada, A.V., Clariá, J.J., Bica, E., & Barbuy, B. 2003, A&A, 408, 287
Frail, D. A. 2003, GCN Circ. 2473 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2473.gcn3)
Fruchter, A. et al. 1999, ApJ, 516, 683
Fryer, C.L., Woosley, S.E., & Hartmann D.H. 1999, ApJ, 526, 152
Fynbo, J. P. U., Jakobsson, P., Möller, P., Hjorth, J., Thomsen, B., Andersen, M. I., Fruchter, A. S., Gorosabel, J., Holland, S. T., Ledoux, C., Pedersen, H., Rhoads, J., Weidinger, M., & Wijers, R. A. M. J. 2003, A&A, 406, L63
Fynbo, J. P. U., Moller, P., Thomsen, B., Hjorth, J., Gorosabel, J., Andersen, M. I., Egholm, M. P., Holland, S., Jensen, B. L., Pedersen, H., & Weidinger, M. 2002, A&A, 388, 425
Gal-Yam, A. et al. 2004, ApJ, submitted (astro-ph/0403608)
Gotz, D., Merghetti, S., Beck, M., & Borkowski J. 2003, GCN Circ. 2459 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2459.gcn3)
Grevesse, N., Noels, A., & Sauval, A.J. 1996, In: Cosmic Abundances, S. Holt and G. Sonneborn (eds.), ASPCS, V. 99, (BookCrafters: San Fransisco), p. 117
Gronwall, C., Salzer, J.J., Sarajedini, V.L., Jangren, A., Chomiuk, L., Moody, J.W., Frattare, L.M., & Boroson, T.A. 2004, AJ, in press (astro-ph/0401132)
Heise, J. 2003, in Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission; AIP Conf. Proc., Vol. 662, p. 229

Henry, R.B.C., Edmunds, M.G., & Köppen, J. 2000, ApJ, 541, 660
Hjorth, J., et al. 2003, Nature, 423, 847
Holweger, H. 2001, in Solar and Galactic Composition, ed. R.F. Wimmer-Schweingruber, (Berlin: Springer), 23
Hsia, C. H., Lin, H. C., Huang, K. Y., Urata, Y., Ip, W. H. & Tamagawa, T. 2003, GCN Circ. 2470 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2470.gcn3)
Izotov, Y.I., Thuan, T.X., Lipovetsky, V.A. 1994, ApJ, 435, 647
Jansen, R.A., Fabricant, D., Franx, M., & Caldwell, N. 2000, ApJS, 126, 331
Kennicutt, R.C., Jr. 1992, ApJ, 38, 310
Kennicutt, R.C., Jr. 1998, ARA&A, 36, 189
Kewley, L.J., Geller, M.J., & Jansen, R.A. 2004, AJ, in press
Kouveliotou, C., et al. 2004, ApJ, submitted (astro-ph/0401184)
Lamareille, F., Mouhcine, M., Contini, T., Lewis, I., & Maddox, S. 2004, MNRAS, in press (astro-ph/0401615)
Le Floc'h, E. et al. 2003, A&A, 400, 499
Lipkin, Y.M., et al. 2003, (astro-ph/0312594)
MacFadyen, A.I. & Woosley, S.E. 1999, ApJ, 524, 262
McClure-Griffiths, N. M., Green, A. J., Dickey, J. M., Gaensler, B. M., Haynes, R. F., & Wieringa, M. H. 2001, ApJ, 551, 394
McLean, Ian S., Graham, James R., Becklin, Eric E., Figer, Donald F., Larkin, James E., Levenson, N. A., & Teplitz, Harry I. 2000, SPIE, 4008, 1048
Melbourne, J. & Salzer, J.J. 2002, AJ, 123, 2302
Mereghetti, S., & Gotz, D. 2003, GCN Circ. 2460 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2460.gcn3)
Mirabal, N., Halpern, J. P., Chornock, R., Filippenko, A. V., Terndrup, D. M., Armstrong, E., Kemp, J., Thorstensen, J. R., Tavarez, M., & Espaillat, C. 2003, ApJ, 595, 935
Nakamura, O., Fukugita, M., Brinkmann, J., & Schneider, D.P. 2004, ApJ, submitted
Neckel, T. & Klare, G. 1980, A&AS, 42, 251
Osterbrock, D.E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (University Science Books, Mill Valley, CA)
Paczyński, B. 1998, ApJ, 494, L45
Perna, R. & Loeb, A. 1998, ApJ, 501, 467
Persson, S.E., Murphy, D.C., Krzeminski, W., Roth, M., & Rieke, M.J. 1998, AJ, 116, 2475
Pettini, M., Shapely, A.E., Steidel, C.C., Cuby, J.-G., Dickinson, M., Moorwood, A.F.M., Adelberger, K.L. & Giavalisco, M. 2001, ApJ, 554, 981
Pian, E., et al. 2000, ApJ, 536, 778
Price, P.A. et al. 2003, Nature, 423, 844
Prochaska, J.X., Chen, H.-W., Hurley, K., Bloom, J.S., Graham, J.R., & Vacca, W.D. 2003, GCN Circ. 2475 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2475.gcn3)
Prochaska, J.X., Bloom, J.S., Chen, H.-W., Hurley, K., Dressler, A. & Osip, D. 2003, GCN Circ. 2482 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2482.gcn3)
Rodriguez-Pascual, P., Santos-Lleo, M. and Gonzalez-Riestra, R., Schartel, N. & Altieri, B. 2003, GCN Circ. 2474 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2474.gcn3)
Rola, C.S., Trelevich, E., & Terlevich, R.J. 1997, MNRAS, 289, 419
Salzer, J.J., Gronwall, C., Lipovetsky, V.A., Kniazev, A., Moody, J.W., Boroson, T.A., Thuan, T.X., Izotov, Y.I., Herrero, J.L., & Frattare, L. M. 2000, AJ, 120, 80
Santos-Lleo, M. and Calderon, P. 2003 GCN Circ. 2464 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2464.gcn3)
Savaglio, S., Fall, S. M., & Fiore, F. 2003, ApJ, 585, 638
Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525
Schmidt, M. 1999, ApJ, 523, L117
Sokolov, V. V., Fatkhullin, T. A., Castro-Tirado, A. J., Fruchter, A., Komarova, V. N., Kasimova, E. R., Dodonov, S. N., Afanasiev, V. L., & Moiseev, A. V. 2001, A&A, 372, 438
Shaw, R.A., & Dufour, R.J. 1995, PASP, 107, 896
Skillman, E.D., Televich, R.J., Kennicutt, R.C., Garnett, D.R., & Terlevich, E. 1994, ApJ, 431, 172
Soderberg, A. M., Kulkarni, S. R. & Frail, D. A., GCN Circ. 2483 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2483.gcn3)
Soderberg, A. M. et al. in preparation
Shapley, A. et al. 2004, in preparation
Stanek, K.Z., et al. 2003, ApJ, 591, 17L
Thomsen, B. et al. 2004, A&A, in press (astro-ph/0403451)
Vaughan,S., et al. 2004, submitted (astro-ph/0312603)
Vreeswijk, P.M. et al. 2001, ApJ, 546, 672
Watson, D., Hjorth, J., Levan, A.,. Jakobsson, P., O'Brien, P.T., Osborne, J.P., Pederson, K., Reeves, J.N., Tedds, J.A., Vaughan, S.A., Ward, M.J., & Willingale, R. 2004, ApJ, submitted
Woosley, S.E. 1993, ApJ, 405, 273
Woosley, S. E., Eastman, R. G., & Schmidt, B. P. 1999, ApJ, 516, 788